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# COATING GLASS FIBRE YARN WITH CONDUCTIVE MATERIALS FOR REAL-TIME STRUCTURE SENSING

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**Keywords:** Coating, Capacitive Sensor, Fibre-reinforced Polymer Composites (FRPC), Structural Health Monitoring (SHM), Physical vapour deposition and Smart material.

**Abstract.** Nowadays, the demand for glass fibre-reinforced polymers (GFRPs) has increased in the industry owing to their low weight, high strength, corrosion resistance and low cost compared with other fibre-reinforced polymer composites. However, GFRP is anisotropic material with low interlaminar strength where the damage can occur without warning. Integrating a real-time damage detection process can mitigate this problem. Therefore, this paper presents the initial fabrication of an embedded capacitive sensor into the GFRP. Two coating methods were considered to form embedded electrodes in this work which include aerosol spray coatings that were carbon based and gold-based physical vapour deposition, (PVD). It has been shown that spray coating has a weak bond and the carbon particles disperse during the molding process. In the PVD technique the nanoparticle (Au) distributed uniformly along the fibres and has a good resistance ( $\approx 100\Omega$ ). The capacitive sensor based on gold coating was examined using a three point bending test which demonstrate linear response toward the flexural load with a sensitivity of 25.1 fF/N.

## Introduction

There is an increasing demand for glass fibre-reinforced polymer (GFRP) among other fibre-reinforced polymer composites in the aerospace industry [1] For example, using GFRP in the structure of an unmanned aerial vehicle (UAV). GFRP is characterized by good flexibility, low cost and a high strength-to-weight ratio. However, GFRP is a heterogeneous material and has a low interlaminar strength. These limitations, in general tend to be subject to degradation in the overall mechanical properties. The degradation can result from unexpected overload, matrix cracking, fibre fragmentation, and delamination between layers. This induced damage may start without warning. Therefore, implementing a real-time in-situ damage detection system is important to anticipate induced defects, which in turn mitigate this problem.

The piezo-resistive sensor is a conventional and traditional sensor for measuring strain in fibre-reinforced polymer (FRP) where carbon nanotubes (CNTs) are generally dispersed in an epoxy matrix to enhance the electrical conductivity [2]. Paleari et al. developed a conductive composite resin where 6 wt% of carbon black was mixed with matrix and, after that, deposited into the surface of glass fibre to obtain self-monitoring plies. This piezo-resistive sensor has a gauge factor of up to 6 [3]. In another study, a three-dimensional electrical sensory network in the composites was investigated for piezo-resistive damage sensing applications by blending carbon nanotubes (CNTs) into an epoxy matrix [4].

Even though the nanomaterials merged with matrix have a high strain gauge factor, the main load in the composite is carried by fibre-reinforcement which can lead to limited information [5]. Moreover, this can produce electromagnetic shielding for FRP, which in turn can prevent transmission signals between onboard and ground systems, particularly in UAVs where telemetry and autopilot data are critical. The integration of electrically conductive materials at the level of glass fibre yarn may allow the electromagnetic signal to be transmitted through the structure. Also, it provides direct strain measurements when the structure is exposed to deformation, as the glass fibre yarn carries the main load. In the previous studies [6][7],  $2 \times 2$  twill weave glass fibre yarn was replaced with carbon fibre yarn to create capacitive electrodes. It has been found that using two types of elastic moduli can cause inter-fibre damage at a low level of stress. Therefore, the possibilities of attaining conductive surfaces of the glass fibre yarn using coating techniques in order to form capacitive electrodes is investigated in this paper. This study considers two coating methods: conventional spraying and physical vapour deposition (PVD). To test the embedded electrodes produced by using coating to form capacitive sensor, a three-point bending test is conducted to initially characterize the capacitive sensor.

## Materials And Methods

**Working Principle Of The Embedded Capacitive Sensor.** As illustrated in Fig. 1(a), the proposed self-sensing glass fibre-reinforced polymer composites are based on parallel plate capacitance. The capacitive sensor consisting of a two-electrode system was embedded in plies 4 and 7, called modified plies, as seen in Figure 1(b). Two electrodes were separated by an unmodified ply (fibreglass woven fabric), which works as the dielectric material. When the GFRP structure is subjected to forces, the integrated sensor will deform in all directions (thickness of the dielectric, width, and length of electrodes), which in turn leads to a change in the capacitance value (strain sensor). Also, the capacitance value can be altered by changing the dielectric constant. For example, induced interfacial damages such as cracks in the epoxy matrix may allow the air to enter between layers, which in turn can alter the effective dielectric (flaws /damage detector) [8]. Also, this type of sensor can be used for detecting water intrusion in composite structures (humidity sensor) where the change of dielectric properties of the material is directly affected by the changing moisture content [9].

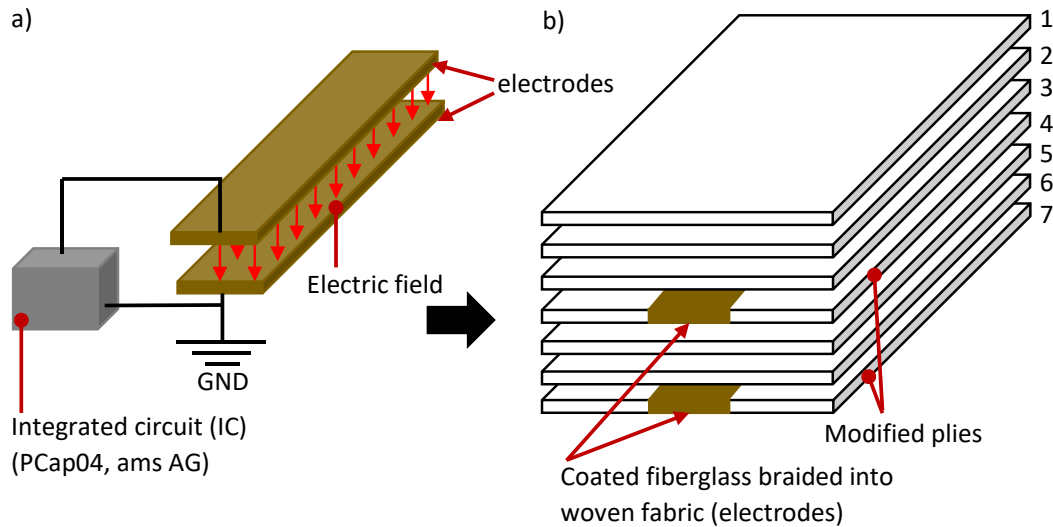


Figure 1: a) schematic diagram of parallel plate capacitor which is equivalent to the proposed embedded capacitance into GFRP. (b) A layup profile used to form the embedded capacitive sensor.

**Preparation Of Coated Fibres For Capacitive Sensing.** In order to produce an embedded capacitive sensor to enable strain monitoring in a woven glass fibre-reinforced polymer composite, the glass fibre yarn was coated to form electrodes. Two conductive coating techniques were implemented in this study as can be seen in Figure 2. The fibreglass yarn ( $2 \times 2$  twill, FK 144, Interglas-92125, Haufler Composites, Blaubeuren, Germany), which was extracted from the weft direction was initially coated using a conventional spray (Carbon Conductive Coating, 340 g, Aerosol Can, M.G. Chemicals Ltd., Canada) as shown in Figure 2 (I). This process was carried out at room temperature, including spraying carbon metal over the yarn of glass fibre and after that using a heat gun for curing coatings, as seen in Figure 2(b) and (c), respectively. After 24 hours, the coated yarn was braided into  $2 \times 2$  twill woven glass fabric as illustrated in Fig. 2 (g), using the integration process described in Figure 2 (f). Figure 2 (i) presents a result of the initial test of the integration between the coated fibres and epoxy matrix, which was conducted using the wet hand lay-up process.

Physical vapour deposition (PVD) was the second approach utilized for the deposition of electrically conductive nanoparticles into the level of fibre yarn. In this process, metal was deposited using an ATC-Orion 8 sputtering system. This system utilizes the magnetron sputtering technique where gold (Au) thin films can be deposited on the substrate, as seen in the schematic diagram of Figure 2 (d). The substrate holder was motorized to have a rotating platform to obtain an excellent coating uniformity and makeup multilayer thin film metal (within a nanometer-thick). The fibre yarns were located in the vacuum chamber to have a coating for around 15 minutes. The process settings used for sputter coating were as follows: chamber pressure of  $6 \times 10^{-3}$  Torr, with a deposition power of 100 W. Figure 2 (e) shows four coated fibre yarns that were 1m long were folded into a spiral shape and accommodated on the substrate. The integration process described in Figure 2 (f) was also used to braid coated fibre into the woven fabric, as seen in Figure 2 (h). To fabricate glass fibre-reinforced polymer composites with modified ply, the hand lay-up technique was also utilized where the final shape of cured laminate is shown in Figure 2 (j).

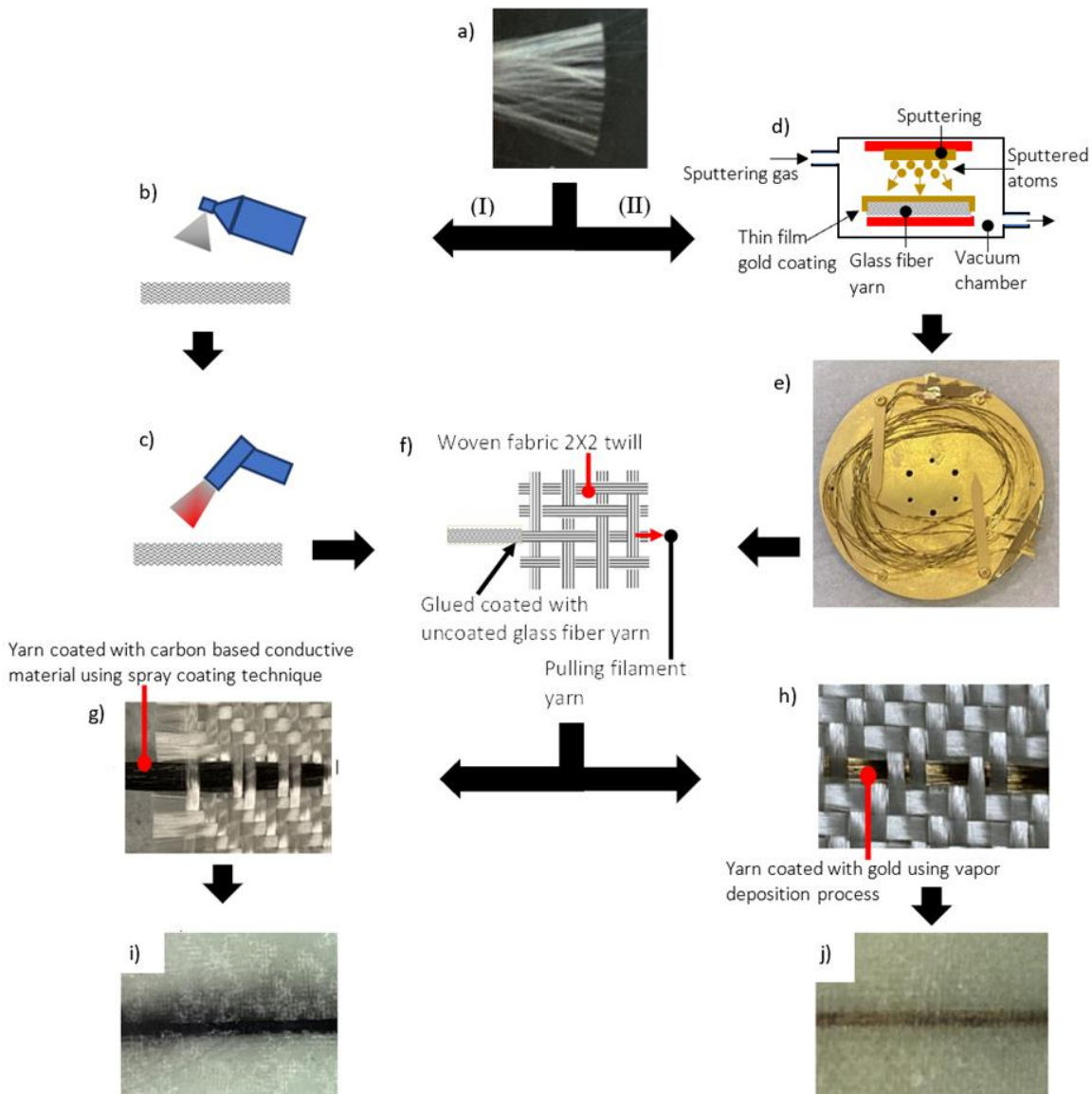


Figure 2: Schematic diagram showing two conductive coating methods for (a) glass fibre yarn: (I) spray coating and (II) Physical vapour deposition (PVD). Conventional spray includes (a) spraying carbon metal and (b) a heat gun for curing. d) Schematic of gold sputtering system. e) image of final shape for coated glass fibre yarns. f) Schematic view of the integration process of coated fibreglass yarn into woven fabric. An image of integrated coated glass fibre yarn into the woven fabric where coatings via (g) the conventional spray and (h) PVD. An image of cured laminates with coated fibreglass yarn using (i) conventional spray and (j) PVD.

**Scanning Electron Microscopy.** For characterization of the coated surface of glass fibre yarn, scanning electron microscopy (JOEL JSM-7600F, FE-SEM, Japan) was utilized, with an accelerating voltage of between 3-5 kV. SEM was conducted on both coated glass fibres to explore surface defects and features using conventional spray and the PVD technique.

**Flexural Test.** The embedded capacitance into GFRP can be used for sensing several physical quantities, as mentioned in section 0. However, the scope of this work is to utilize the capacitive sensor to measure the deformation when the structure is exposed to forces. To initially characterize the performance of the self-sensing GFRP, a three-point bending test was performed. To complete the flexural test experiment, the sample with a width of 22.22 mm and thickness of 1.95 mm was loaded on test equipment which shown in Figure 3. A universal load cell (LCM202-500N) from OMEGA was used to measure the flexural force exerted on the sample. To measure the relative change in capacitance, two wire sensors were connected to a commercially available integrated circuit (PCap04, ams AG) with a sampling rate of 12.5 Hz.

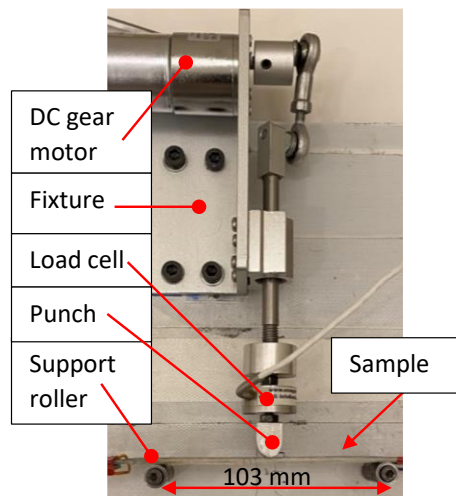


Figure 3: Experimental setup of the three-point bending test

## Results And Discussions

The key novelty in this work is to form an embedded capacitive sensing electrode through coating glass fibre yarns for enabling strain monitoring in  $2 \times 2$ -twill woven fabric composites. To investigate this capability of the proposed sensor, the structural features of the two coatings method were visually inspected using SEM. In addition, the three-point flexural test was initially conducted to perform the basic characterization and provide self-sensing functionality of the smart structure.

The morphologies of the coated yarn and single filament for both spray coating (carbon-based coating) and PVD are shown in Figure 4. The SEM image was set to low magnification to visualize the result of spraying an electrically conductive layer over glass fibre yarn, as shown in Figure 4 (a). It is clear that there are unwanted fibre agglomerates that were produced by spray coating (carbon). This agglomeration causes the yarn to be inflexible, increasing the difficulty of braiding into woven fabric. Also, this may prevent the epoxy resin from completely penetrating into the fibres (coated filaments) during the wet layup process, which can affect the mechanical properties of the composite. Incorporation of carbon-based coated yarn into epoxy resin was examined, and the result is shown in Figure 2 (i). It is shown that the coating was dispersed into the polymer matrix composite. This can be attributed to a weak adhesion between the coating and the fibreglass which can be seen in Figure

4 (b). To address these issues, an Au thin film deposition was carried out using the PVD technique for coating glass fibre yarn. This technique showed a good result. The low magnification image of Au coating shows that there was no adhesion between single filaments (fibres), as seen in Figure 4 (c). In addition, the mechanical flexibility of the coated yarn was not affected by the PVD, which made the integration process much easier. The low magnification image for the single filaments illustrates that deposition of electrically conductive nanoparticles of Au can cover the fibre surface with uniform coating as seen in Figure 4 (d). Further detail of the compression between carbon-based coating and the PVD technique is given in Table 4.

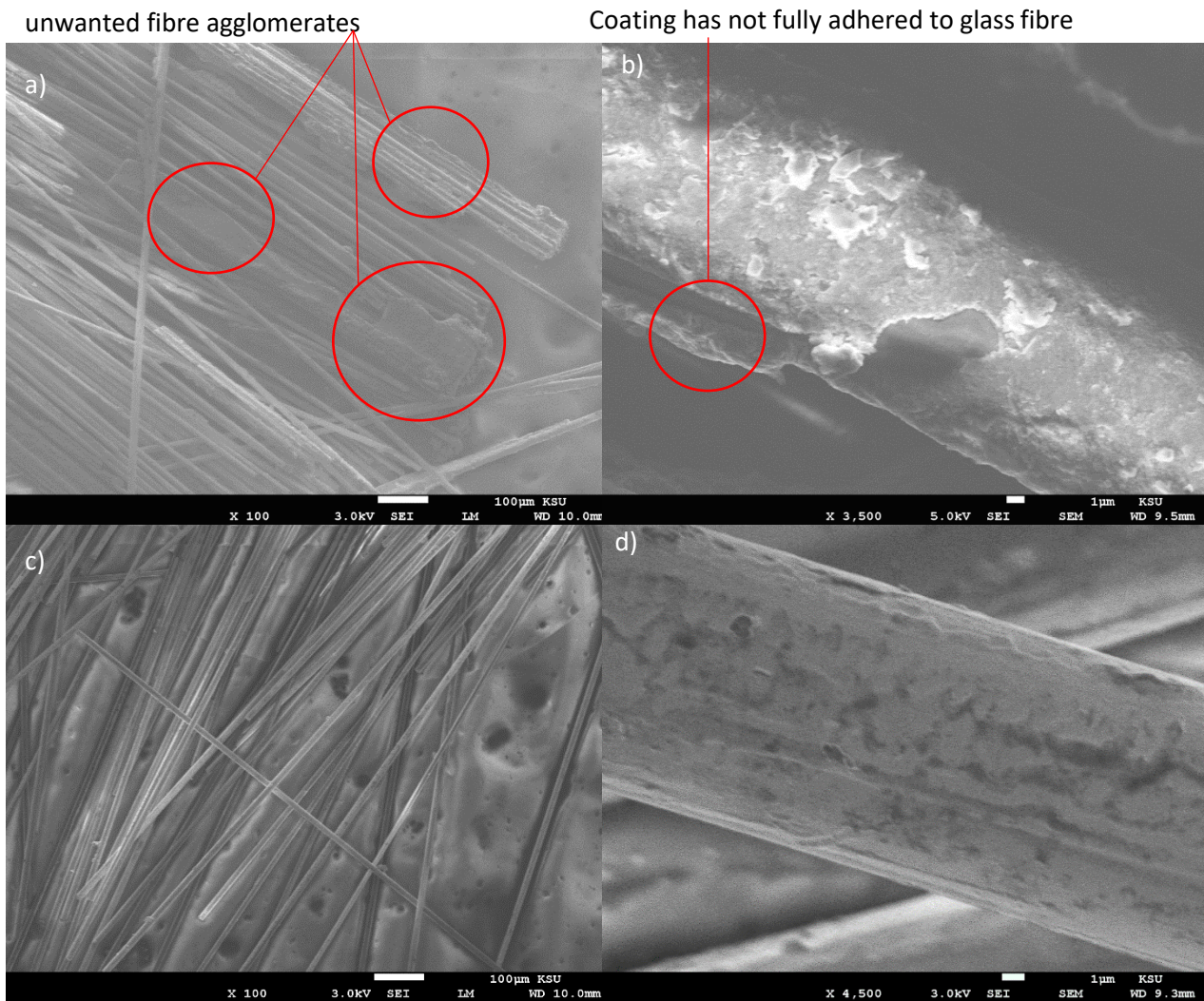


Figure 4: SEM image of coated glass fibre yarn using (a) spray carbon conductive coating and (c) PVD. SEM micrographs of coated single filament using (b) Spray carbon conductive coating and (d) PVD.

Table 1: Comparison between coated yarn using the aerosol spray based on carbon and the PVD coating technique.

Deposition method	Material	Advantages	Disadvantages
Aerosol spray coating	Carbon	<ul style="list-style-type: none"> <li>• Coating can be conducted out at room temperature</li> <li>• Suitable for long filaments</li> <li>• Low cost</li> </ul>	<ul style="list-style-type: none"> <li>• Fibre agglomerates</li> <li>• Poor adhesion</li> <li>• Coating can vary along filaments</li> <li>• Coating disperses during curing, see Figure 2 (i)</li> <li>• High resistance (<math>\approx 120 \text{ k}\Omega</math> for 1m of coated glass fibre yarn).</li> <li>• Coated yarn is not flexible compared to PVD technique</li> </ul>
PVD	Gold (Au)	<ul style="list-style-type: none"> <li>• Muti filaments can be coated at the same time as shown in Figure 2 (e)</li> <li>• Uniform coating, see Figure 4 (d)</li> <li>• No fibre agglomerates</li> <li>• Coated yarn is easily integrated into woven glass fibre</li> <li>• Coated yarn has the same width of pristine yarn, see Figure 2 (h).</li> <li>• Relatively low resistance (<math>\approx 100 \text{ }\Omega</math> for 1 m of coated glass fibre yarn)</li> <li>• Good adhesion</li> <li>• Coating has not spread after curing</li> </ul>	<ul style="list-style-type: none"> <li>• Expensive</li> <li>• Need a sophisticated instrument to carry out coating</li> </ul>

While carbon-based spray coating was able to provide valuable insight for forming embedded electrodes into woven glass fibre, it was subject to some limitations as summarized in Table 1. Therefore, the second approach was adopted for yarn coating, and the basic characterization of the embedded capacitive sensor was conducted. The sample was loaded in a three-point bending test to obtain the relative change in the capacitance against flextural load. The electrodes were integrated in layers 4 and 7 as described in section 0. The initial capacitance was measured to be around 23 pF. In order to investigate the sensitivity of the capacitive sensor in bending mode, the sample was loaded with varying step loads up to 29 N, and the output result is shown in Figure 5(a). It has been shown that the the relative change in capacitance increased with increasing flexural load. To find the sensivity of the capacitive sensor, a least-squares method (LSM) was implemented to fit the experimental test data, as shown in Figure 5 (b), and then the slope was determined to be 25.1 fF/N. It is clear that the capacitive sensors exhibit linear sensitivity to the crosshead load where the coated fibre, using the PVD technique, has given sensing ability to load monitoring.



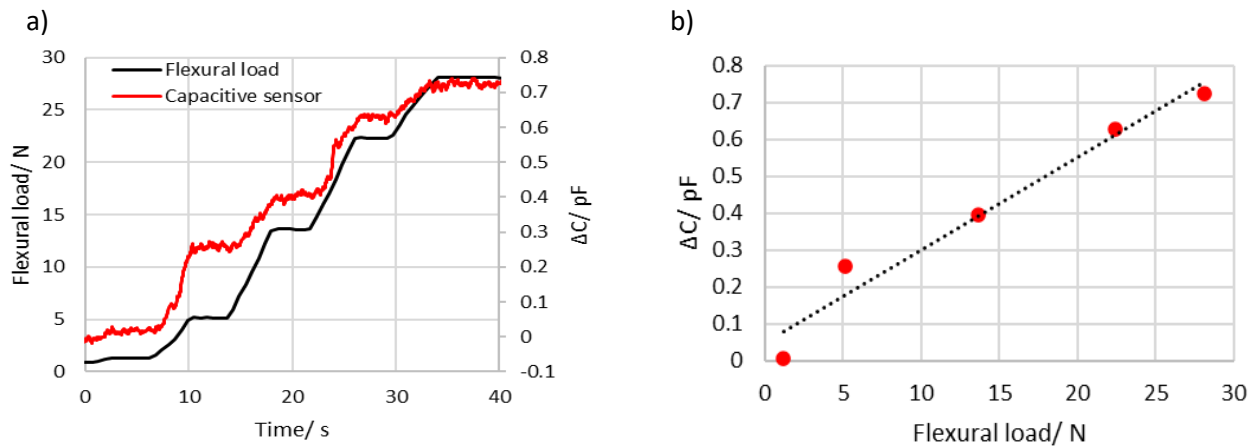


Figure 5: (a) Time history of flexural load and relative change in capacitance under variable amplitude loading. (b) Relative change in capacitance against the flexural load of three point bending test.

## Conclusion

In this paper, in situ structural health monitoring based on capacitive sensor was developed for glass fibre reinforced polymer. Two techniques of fibre coating were considered in this study to form electrodes of the capacitive sensor which include carbon-based aerosol spray and the PVD. The structural features of the coated fibre was investigated and demonstrated using SEM. To initially characterize the fabricated electrodes (gold based) of the capacitive sensor to enable strain monitoring, a three point bending test was conducted where the sample was deflected with varying loads up to 29 N and the reading from the capacitive sensor was recorded. Based on the experimental tests, the main findings can be summarised as follows:

- Using the aerosol spray (carbon-based) was found to have high electric resistance, poor adhesion and also resulted in the development of unwanted dispersed carbon particles in the epoxy matrix.
- The PVD technique which utilized the deposition of nanoparticles (Au) showed a uniform coating along the fibres, good adhesion and low resistance compared with spray coating.
- The developed smart material showed linear sensitivity toward crosshead load where the estimated sensitivity was 25.1 fF/N.

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